

Development of Improved Algorithms and Multiscale Modeling Capability with SUNTANS

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LONG-TERM GOALS

The long-term goal is to develop a nonhydrostatic, parallel ocean simulation tool that is capable of simulating processes on a wide range of scales through use of accurate numerical methods and high-performance computational algorithms. The tool will be applied to study highly nonlinear internal waves in coastal domains to develop an improved understanding of mechanisms that govern their generation, propagation, and dissipation.

OBJECTIVES

The primary objective is to enhance the capabilities of the SUNTANS model through development of algorithms to study multiscale processes in estuaries and the coastal ocean. This involves development of 1) improved momentum and scalar advection on unstructured, staggered grids, 2) accurate and efficient algorithms for solution of the nonhydrostatic pressure, and 3) adaptive grid capabilities with adaptive mesh refinement and model nesting.

APPROACH

This work focuses on the continued development of SUNTANS (Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator), a free-surface, nonhydrostatic, unstructured-grid, parallel coastal ocean and estuary simulation tool that solves the Navier-Stokes equations under the Boussinesq approximation (Fringer et al., 2006). The formulation is based on the method outlined by Casulli and Walters (2000), in which the free-surface and vertical diffusion are discretized with the theta method which eliminates the Courant condition associated with fast free-surface waves and the elevated friction term associated with small vertical grid spacing at the free-surface and bottom boundary. For flows with extensive wetting and drying, advection of momentum is accomplished with the semi-Lagrangian advection scheme (Wang et al. 2011a), which ensures stability in the presence of cells that fill and empty with the tides. Scalar advection is accomplished semi-implicitly and continuity of volume and mass are guaranteed for the hydrostatic solver, following Gross et al. (2002). The theta method for the free-surface yields a two-dimensional Poisson equation, and the

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nonhydrostatic pressure is governed by a three-dimensional Poisson equation. These are both solved with the preconditioned conjugate gradient algorithm with Jacobi and block-Jacobi preconditioning, respectively. Because the nonhydrostatic component of SUNTANS is essentially a correction to the hydrostatic component, SUNTANS can be run seamlessly in nonhydrostatic or hydrostatic modes. SUNTANS is written in the C programming language, and the message-passing interface (MPI) is employed for use in a distributed-memory parallel computing environment. SUNTANS employs the generalized length scale approach to Reynolds-averaged turbulence modeling (Wang et al. 2011b). The SUNTANS grid employs z-levels in the vertical and is unstructured in plan, which enables the resolution of complex coastlines and topographic features. Unstructured grids also enable the use of high grid resolution in regions of interest while coarsening the grid in regions where grid resolution is not required, thereby significantly reducing computational overhead.

WORK COMPLETED

We have begun the development of a nonhydrostatic isopycnal-coordinate model and have developed methods to filter unwanted grid-scale oscillations associated with C-grid discretizations on unstructured grids. Stability of the nonhydrostatic algorithm that is implemented in SUNTANS has also been proven. We have tested SUNTANS ability to predict internal wave generation at an idealized ridge and the results match theoretical predictions. Below we focus on the nonhydrostatic isopycnal method and the internal wave generation results.

RESULTS

Nonhydrostatic isopycnal-coordinate model

The paper by Vitousek and Fringer (2011) indicates that accurate resolution of internal solitary waves requires a horizontal grid spacing that is less than the mixed-layer depth. For domains like the South China Sea, this requires $O(100 \text{ million})$ grid cells just to begin to capture the longest nonhydrostatic waves. To reduce the computational expense associated with accurately simulating nonhydrostatic solitary waves, we have begun developing a nonhydrostatic isopycnal coordinate model, following the success and efficiency of traditional (hydrostatic) isopycnal coordinate models applied to the South China Sea (Simmons et al. 2011).

Like any nonhydrostatic solver, the numerical method we employ requires the solution of an elliptic equation for the nonhydrostatic pressure, which significantly increases the computational effort. However, because most of the internal wave energy is contained within the first baroclinic mode, the isopycnal approach gains efficiency by reducing the required number of vertical grid points from $O(100)$ grid points in traditional ocean models (as in Zhang et al. 2011) to $O(1)$, thereby reducing the total number of grid cells for the South China Sea problem to a more tractable value of $O(1 \text{ million})$. Another clear advantage of moving grid or isopycnal models is that they reduce or eliminate spurious diapycnal mixing (Griffies et al. 2000, Koltakov and Fringer 2012). Isopycnal models should also eliminate the spurious energy loss that occurs during solitary wave formation that was diagnosed by Hodges et al. (2006).

Our model formulation is based on that described in Casulli (1997) in which the free surface, vertical diffusion, and isopycnal layers are discretized implicitly with the theta method. To accommodate the

nonhydrostatic pressure in our model, the baroclinic terms are discretized explicitly in time with the third-order Adams-Bashforth method. The wetting and drying of isopycnal layers is made possible by the use of Multidimensional Positive Definite Advection Transport Algorithms (MPDATA; Smolarkiewicz and Margolin, 1998). These methods ensure positive layer heights provided the advective Courant number is less than unity. The model is currently being developed for structured grids, however the approach could easily be extended to unstructured grids and implemented as an option in SUNTANS.

Adcroft and Hallberg (2006) outlined an approach to nonhydrostatic modeling in isopycnal coordinates. However, they ultimately concluded that such an approach was “pointless since non-hydrostatic effects tend to be associated with over turning (e.g. Kelvin–Helmholtz instabilities).” However, we believe that our approach is essential for accurate resolution of nonlinear and nonhydrostatic internal solitary waves. Although the model is in its early stages of development, it is already capable of forming well-resolved and physically realistic nonlinear internal solitary waves in idealized test cases, as shown in Figure 1.

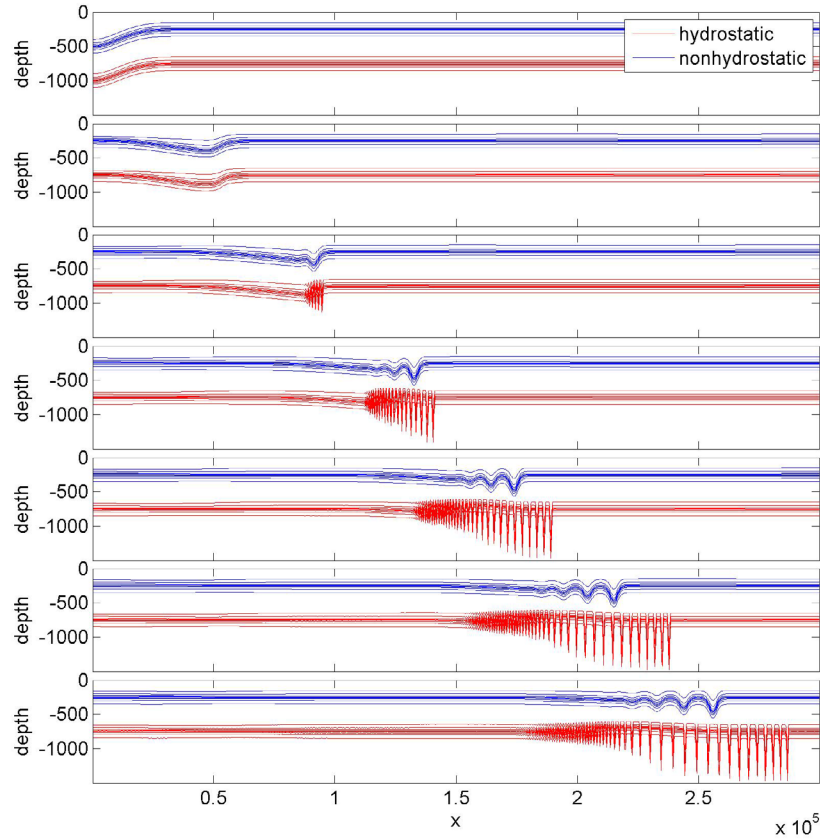


Figure 1: Comparison of the evolution of a solitary-like wave using the hydrostatic isopycnal model (red) and the nonhydrostatic isopycnal model (blue) with the horizontal grid resolution equal to the upper mixed-layer depth (similar to the test case from Vitousek and Fringer 2011). The nonhydrostatic isopycnal model forms physically realistic solitary waves while the hydrostatic model forms waves that are too large and narrow.

We have developed a code based on the formulation of Kang and Fringer (2012) to calculate internal wave energy radiation from a model ridge in the SUNTANS model. The results show the variation of the linear internal wave energy flux as a function of the tidal excursion parameter (ε_2 =tidal excursion/topographic scale) for three different slope regimes based on the value of the criticality parameter (ε_1 =Topographic slope/Internal wave beam slope). Because linear theory is restricted to small tidal excursions (linear flow), small topographic slopes (subcritical slope), finite water depth, and simple topography shapes (e.g. Witch of Agnesi profile; St. Laurent et al. 2003), we compare the SUNTANS results to those from the Green's function approach which extends linear theory to topographies of arbitrary shapes and slopes (Petrelis, 2005; Echeverri and Peacock, 2011). The iTides model (Echeverri and Peacock, 2011) is used to compute theoretical predictions of internal wave energy flux for comparison to the SUNTANS model.

To compare the results of SUNTANS to those of the iTides model (Echeverri & Peacock, 2011), all terms in the SUNTANS model are linearized except for the bottom boundary condition. A semidiurnal barotropic tide is forced over a Gaussian ridge with a height of $h_0=50$ m and width of 12 km in a constant stratification such that the slope of the internal tidal beams is 1.6° . The SUNTANS domain is two-dimensional with a length $L = 1400$ km and depth $H = 1000$ m, with a horizontal grid resolution of 2 km, a vertical grid resolution of 8.3 m (120 vertical grid cells), and a time step size of 120 s. As shown in Figures 2-4, excellent agreement is obtained between SUNTANS and iTides for various values of the slope and excursion parameters. The parameters shown in Figures 3 and 4 are the same as those in Figure 2 except that in the critical case $H = 3500$ m and $h_0 = 205$ m and in the supercritical case $H = 4500$ m and $h_0 = 300$ m. The SUNTANS model results match those of iTides to within 1%. As shown in Figure 5, when the nonlinear and nonhydrostatic terms are included in the SUNTANS model, SUNTANS produces energy fluxes that are smaller than those of iTides. We are analyzing the terms in the energy flux budget to determine the physical reasoning behind this discrepancy.

IMPACT/APPLICATIONS

High-resolution simulations using nonhydrostatic models like SUNTANS are crucial for understanding multiscale processes that are unresolved, and hence parameterized, in larger-scale ocean models.

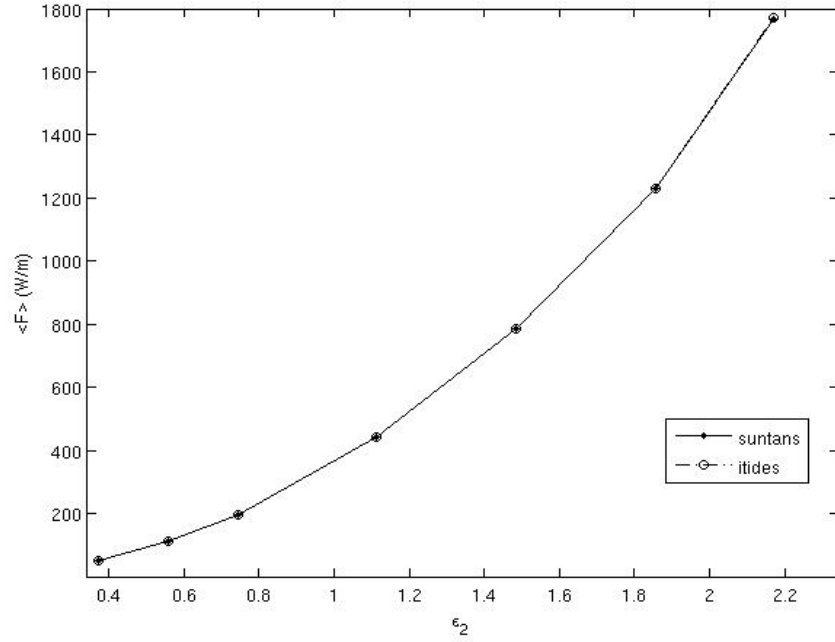


Figure 2: Comparison of internal tide energy flux using hydrostatic and linear SUNTANS (solid line) and iTides (dashed line) for a subcritical Gaussian ridge.

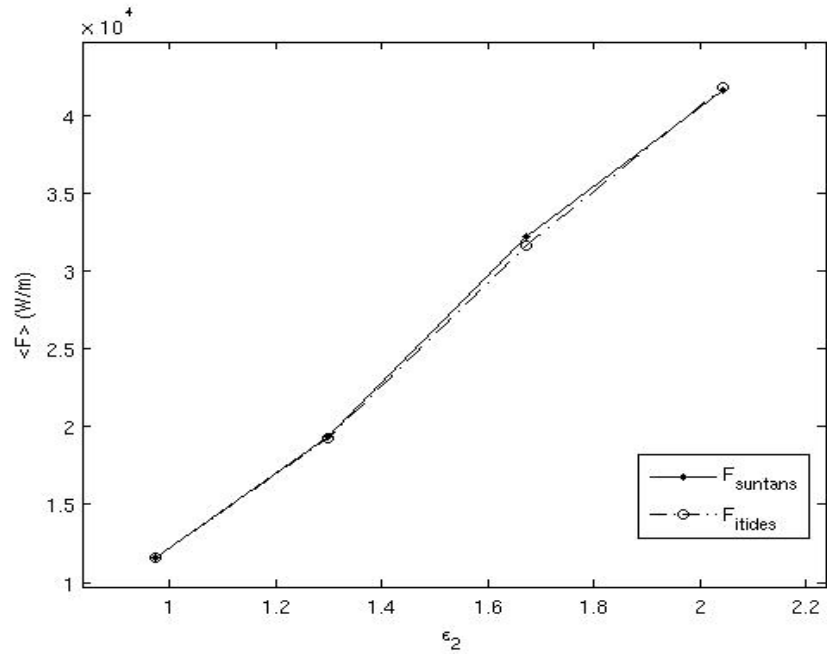


Figure 3: Comparison of internal tide energy flux using hydrostatic and linear SUNTANS (solid line) and iTides (dashed line) for a critical Gaussian ridge.

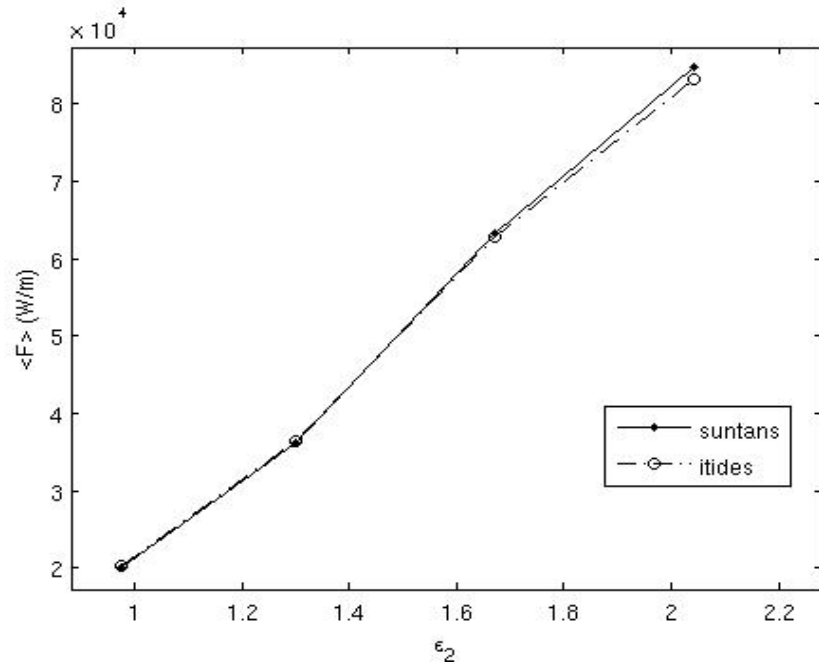


Figure 4: Comparison of internal tide energy flux using hydrostatic and linear SUNTANS (solid line) and iTides (dashed line) for a supercritical Gaussian ridge.

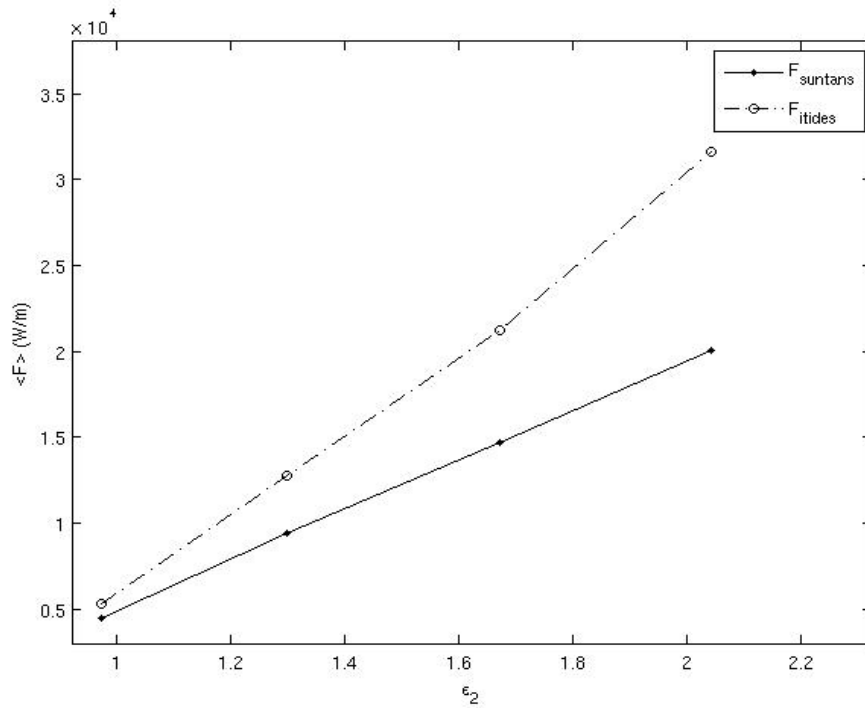


Figure 5: Comparison of internal tide energy flux using nonhydrostatic and nonlinear SUNTANS (solid line) and iTides (dashed line) for a critical Gaussian ridge.

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